Eddy currents induced by Villari-Effect in actual magnetostrictive materials

D. Davino, A. Giustiniani, C. Visone

I. INTRODUCTION

In recent years several devices employing materials with strong electro- or magneto-mechanical coupling have been conceived for the recovery of environmental energy. Such task, known as *energy harvesting*, allows to convert energy from mechanical vibrations which is almost everywhere available (vibrations from vehicles, buildings, human activity, etc.), into electrical energy with a sufficient amount and rate to supply several devices. This pushed to propose a large number of challenging solutions able to supply those devices operating in conditions where electrical energy is unavailable.

Among them, magnetostrictive-based energy harvesting devices along with simplified linear modelling have been proposed [1], [2]. In such devices the electromechanical conversion mechanism is founded on the *Villari effect*, which consists in the change of magnetization due to the variation of the mechanical stress applied to the material. Unfortunately, the global behavior of these materials is quite far from linearity, so a more general modelling was required to realistically describe the energy conversion mechanism, [3]. Since all magnetostrictive materials are conductors the magnetization induced by mechanical load variations leads to non negligible *eddy currents* phenomena which yield a degradation of the harvesting device performances. All studies proposed so far were carried out in linear conditions. The present paper is therefore aimed to propose a more realistic model of eddy currents, induced by load variations, by taking nonlinearities and hysteresis into account.

II. NONLINEAR FULLY COUPLED MODEL

A simple concept device is shown in Fig. 1, where the magnetostrictive rod has a cross section $S = \pi b^2$, a length l and volume $V = lS$, while N is the coils turn number. The rod undergoes compressive stress $F_1(t)$ with a tip velocity $v_1(t)$. The force produces a stress distribution inside the rod that is assumed as uniform ($T(t) = T_0 + T_m \cos(\omega t)$). In the linear case the coupling between magnetic and mechanical variable is as follows: $H_T = \frac{1}{\mu}B - \frac{d}{\mu}T$, being B the magnetic induction, T the applied uniform stress and H_T is the total magnetic field. The coefficient d is the linear piezo-magnetic cross-coupling and μ is the magnetic permeability. In this paper the following *scalar* and static characteristic is assumed: $H_T = \mathcal{H}(B,T)$, where $\mathcal{H}$ is a operator with hysteresis. If now $b << l$, the

D. Davino and C. Visone are with Dipartimento di Ingegneria, Università degli Studi del Sannio, I-82100 Benevento, Italy, email: {davino,visone}@unisannio.it

A. Giustiniani is with the DIIIE, Università degli Studi di Salerno I-84084 Fisciano (SA), Italy, email: agiustiniani@unisa.it
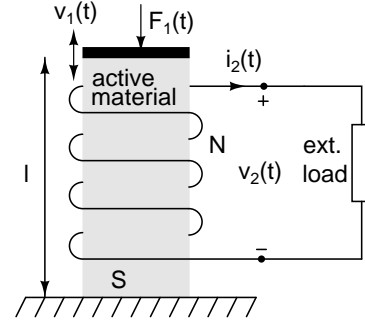

Fig. 1. Sketch of the concept device

following 1-D diffusion problem can be formulated:

$$\frac{\partial}{\partial r}\mathcal{H}\left(\frac{1}{r}\frac{\partial}{\partial r}(rA)\right) = \sigma \frac{\partial A}{\partial t}, \qquad (1)$$

being σ the electric conductivity of the magnetostrictive material. It is reasonable to assume that the induction is completely inside the rod (i.e. zero induction outside the rod). Further, if $H_T = H + H_0$, being H_0 a superimposed *bias* magnetic field, and $v = Ri$ the characteristic of a resistive load, the following boundary conditions hold:

$$\mathcal{H}(B,T)]_{r=b} = -\frac{2\pi b N^2}{Rl}\dot{A}(r=b,t) - H_0 \qquad (2)$$

$$A(r=0,t) = 0. \qquad (3)$$

Finally, the following initial condition is assumed:

$$A(r,t=0) = 0. \qquad (4)$$

The case $\sigma = 0$ yields the model considered in [3], which describe with quite accuracy the mechanism of electromechanical conversion taking place in the device. In the complete manuscript, both the model describing the magneto-mechanical coupling and the governing equation will be described in detail. The complete model will be so exploited to describe the energy loss mechanism due to eddy currents generated by a time variation of the applied mechanical load and affecting the global performances of the device.

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